Characterizing Performance and Errors of Coarse Sun Sensors

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Overview

Performed a study on the feasibility of using off-the-shelf photodiodes as coarse sun sensors for in-orbit attitude determination.

Investigated what other institutions have done for sun sensor attitude determination.

Tested two different configurations and their respective performance/precision.

Proposed a possible configuration for the EXACT and SOCRATES missions.

Attitude Determination with Sun Sensors

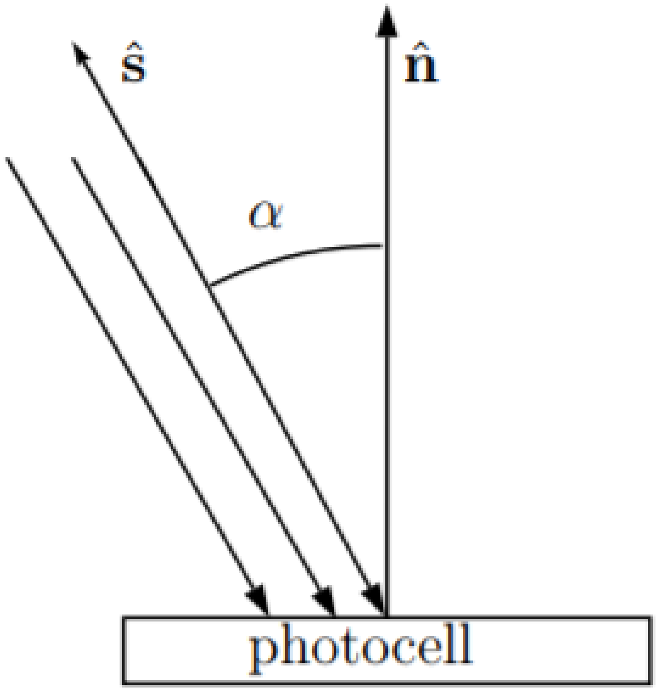
An attitude solution can be obtained by using the measured sun vector, relative to the body frame, and the sun vector prediction from a model, relative to the NED frame in our case.

Voltage/Current in a sun sensor varies with incidence angle. This known relation can be used to estimate a sun vector.

What is needed:

- Significant sun sensor coverage in the satellite
- Solar model
- Earth's albedo model
- In-orbit calibration

Voltage/Current Relation in Sun Sensors



The incidence angle of the photons interacting with the sun sensors have a direct effect on the voltage and current measured:

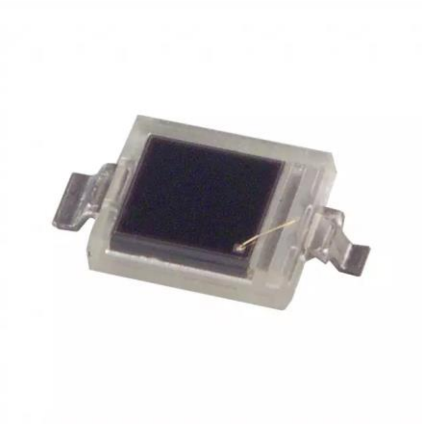
$$I(\alpha) = I_o \cos\alpha$$

$$V(\alpha) = V_o \cos\alpha$$

The incidence angle can be obtained from these relations and then utilized to compute a sun vector estimate.

Similar relationship exists for solar panels.

Coarse Sun Sensor vs Fine Sun Sensors



Coarse Sun Sensors

Less accurate

Design for any application requiring sun sensors

Cheap (~ $1.50 per sensor)

Fine Sun Sensors

Optimized for attitude determination

Higher accuracy

Higher price (~ $3,500 per sensor)

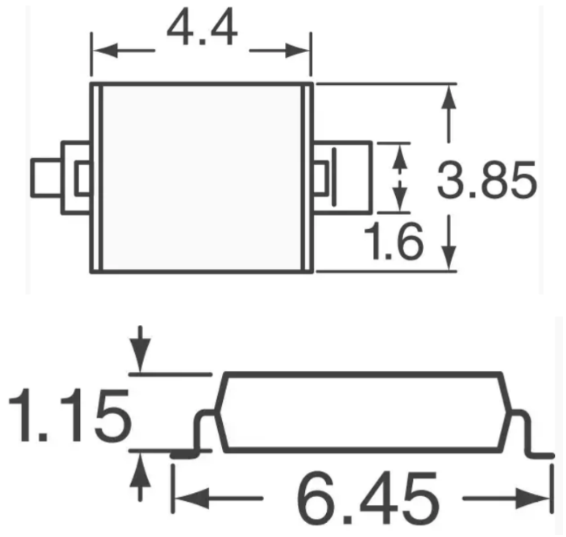
Sun Sensor Selected

SFH 2430-Z Photodiode by OSRAM Opto Semiconductors Inc.

- Relatively cheap ($1.52) compared to Fine Sun Sensors
- Has space heritage with the RAX-1 and RAX-2 satellites from the University of Michigan.
- Small size allows for multiple configurations to be tested.

Open circuit voltage of ~0.317V.

- Noise from the photodiodes is minimal.
- Signal has to amplified to “readable” levels for the flight computer.



Configurations from other Institutions

NUTS satellite by the Norwegian University of Science and Technology

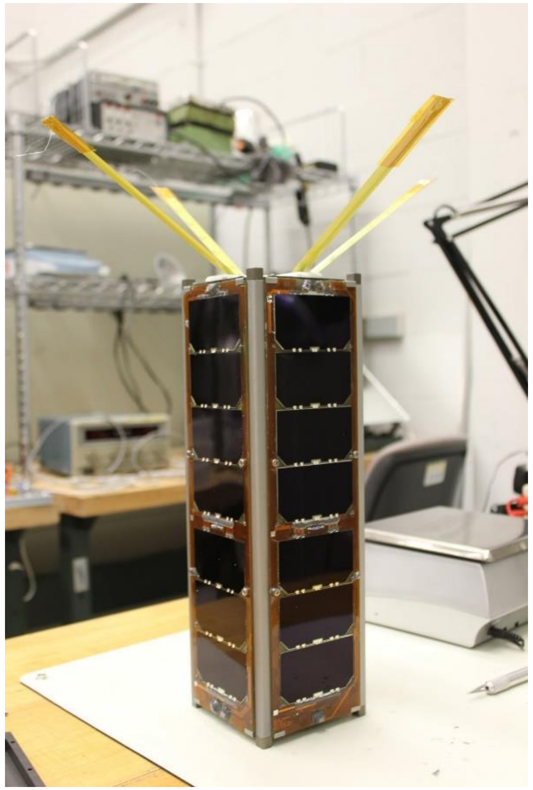
- 2U CubeSat
- Solar panels on all faces except the front.
- Utilized the solar panels themselves to predict the incidence angle of the sun on the panel.

RAX-1 and RAX-2 satellites by the University of Michigan

- 3U CubeSat
- Solar panels on all faces except front and back.
- RAX-1 had photodiodes mounted flat on each surface of the satellite.
- RAX-2 had photodiodes mounted on 14 different angled orientations to increase coverage.

EXACT and SOCRATES constraints

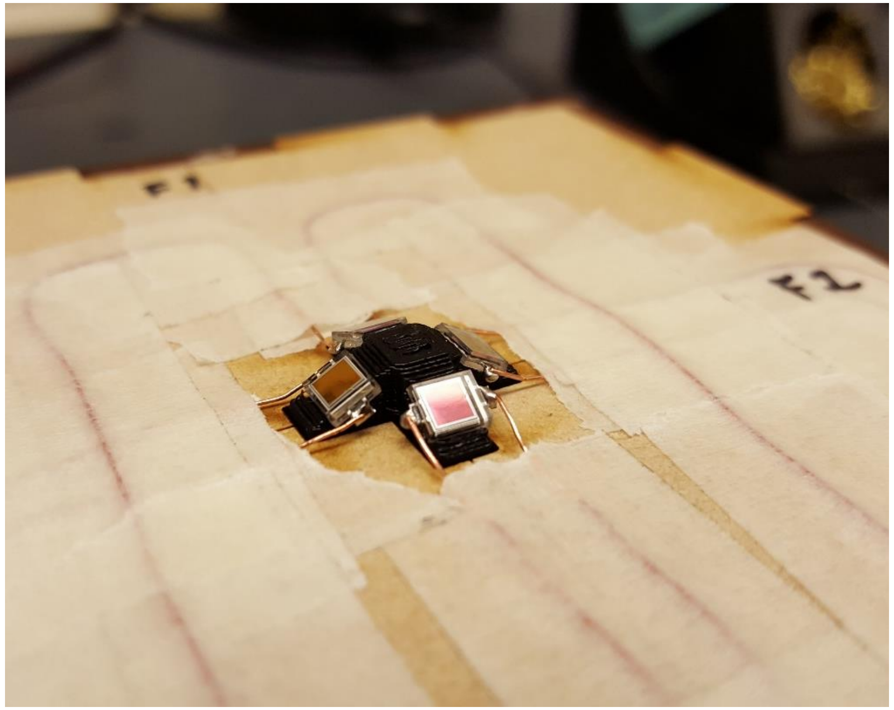
- Both satellites have a particular solar panel configuration not found on most 3U CubeSats.
- Shadows due to the “flower petal” deployment of the panels increase the complexity of the sun sensor configuration.
- Detector placement limits the available locations for sun sensors.
- Structure already designed, so the configuration will have to be as less invasive as possible.
- Boards already designed, so the circuit has to be as simple as possible.
- Configurations like that of RAX-1 and RAX-2 (on the right) will not be useful for EXACT or SOCRATES.



Tested Configurations

Single Photodiode per Face

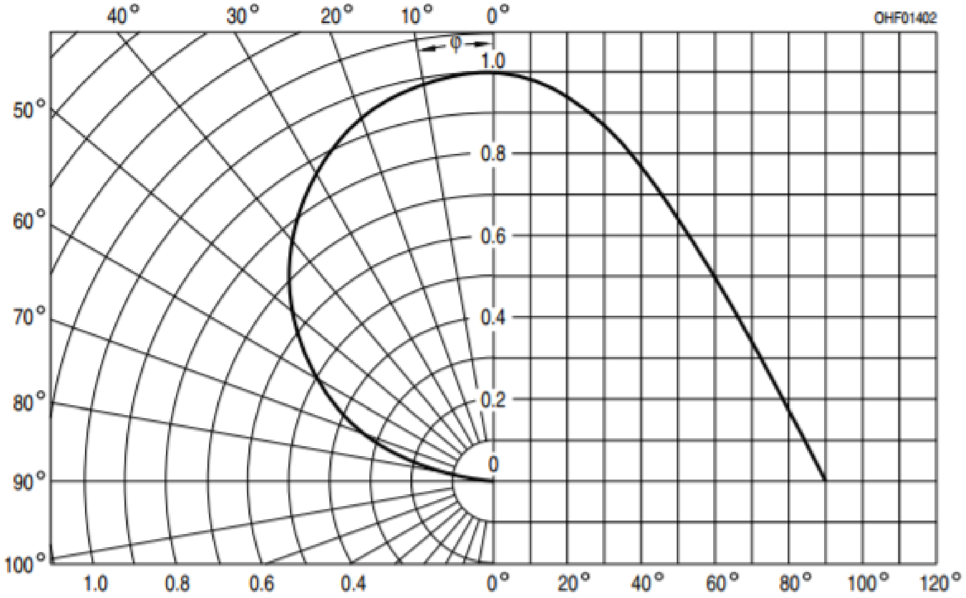
Photodiode Pyramid



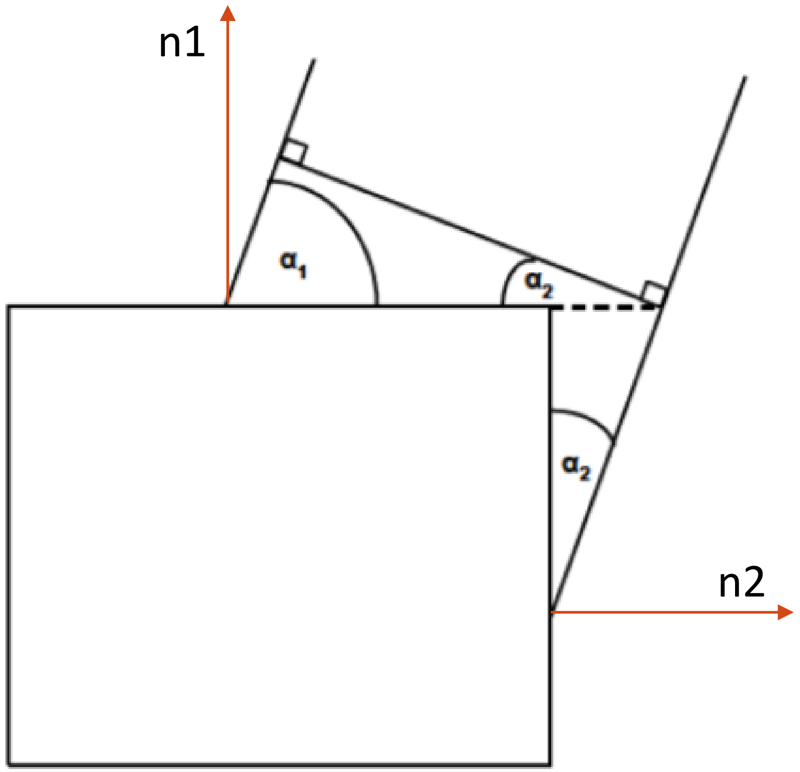
Single Photodiode per Face

Basic Idea:

- Look at the interception of orthogonal components of incident rays and use geometry to solve for the vector.
- Somewhat accurate for small angles of incidence but accuracy increases with the angle.
- Field of view of the sensor only limited by the sensitivity of the sensor itself (diagram on the right). After a certain threshold the sensor is not sensitive enough to provide valuable outputs.
- Two equations: Conical approach or triangle approach.
- Our approach was adapted from the NUTS satellite.



Single Photodiode per Face Equations



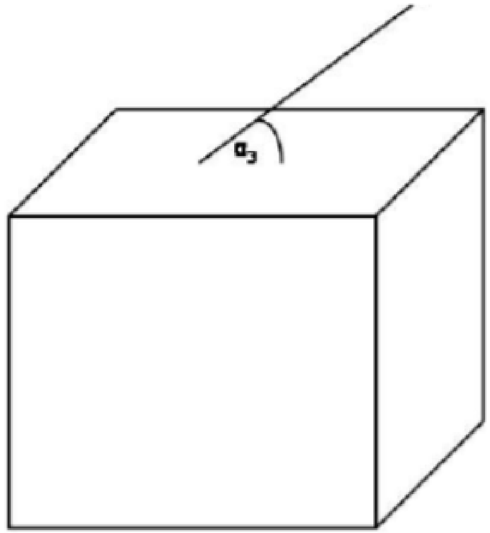
$$V_1 = V_o \sin \alpha_1$$

$$V_2 = V_o \sin \alpha_2$$

$$\begin{bmatrix} \sin \alpha_1 \\ \sin \alpha_2 \end{bmatrix} = \begin{bmatrix} \frac{V_1}{V_{o1}} \\ \frac{V_2}{V_{o2}} \end{bmatrix}$$

Allows for the individual characterization of the max output for each sensor. We will be assuming that this is 5V for all sensors (after amplifying).

Single Photodiode per Face Equations



Follows similar principle as 2D, it just takes into account the rotation about the z axis of the cube.

$$V_1 = V_o \sin \alpha_1 \cos \alpha_3$$

$$V_2 = V_o \sin \alpha_2 \cos \alpha_3$$

$$V_3 = V_o \sin \alpha_3$$

$$\begin{bmatrix} \sin \alpha_1 \cos \alpha_3 \\ \sin \alpha_2 \cos \alpha_3 \\ \sin \alpha_3 \end{bmatrix} = \begin{bmatrix} V_1/V_o \\ V_2/V_o \\ V_3/V_o \end{bmatrix}$$

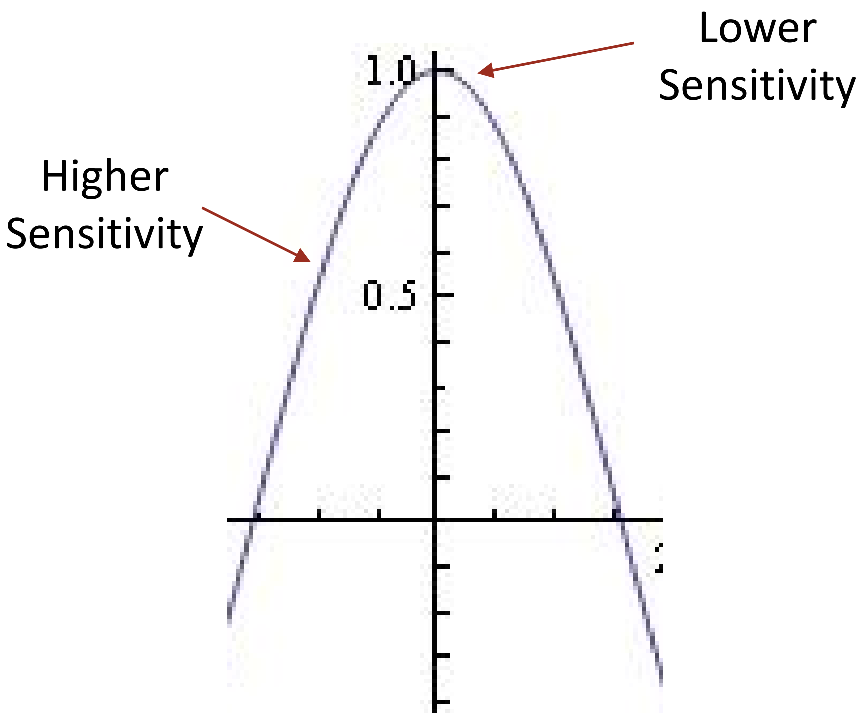
We define our own axis so this can be done with respect to the satellite's body frame.

- Note, we neglected the conical approach due to redundancy.

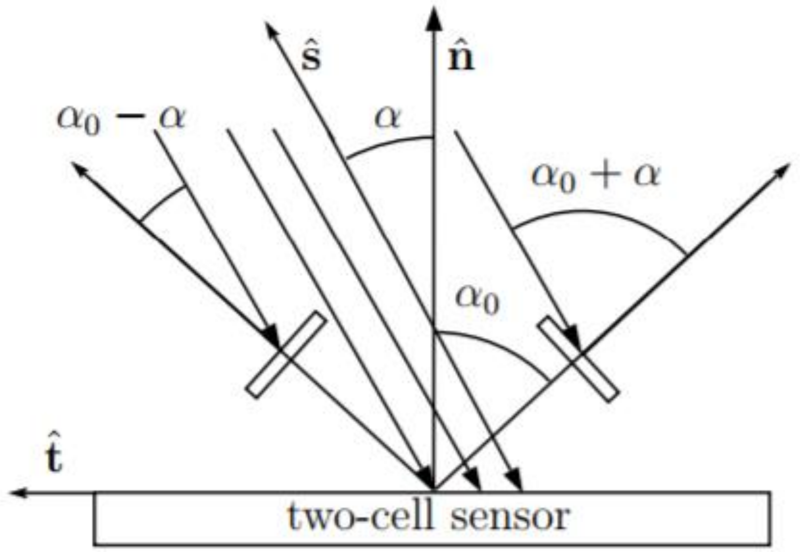
Photodiode Pyramid

Basic Idea:

- Incline the photodiode at a default angle α_o relative to the horizontal so that the sensor is in a higher sensitivity region.
- Increases sensitivity for small angles of incidence but increases error for higher angles.
- Algorithm used for this configuration creates a Field of View for the sensor pyramid that cannot be exceeded.



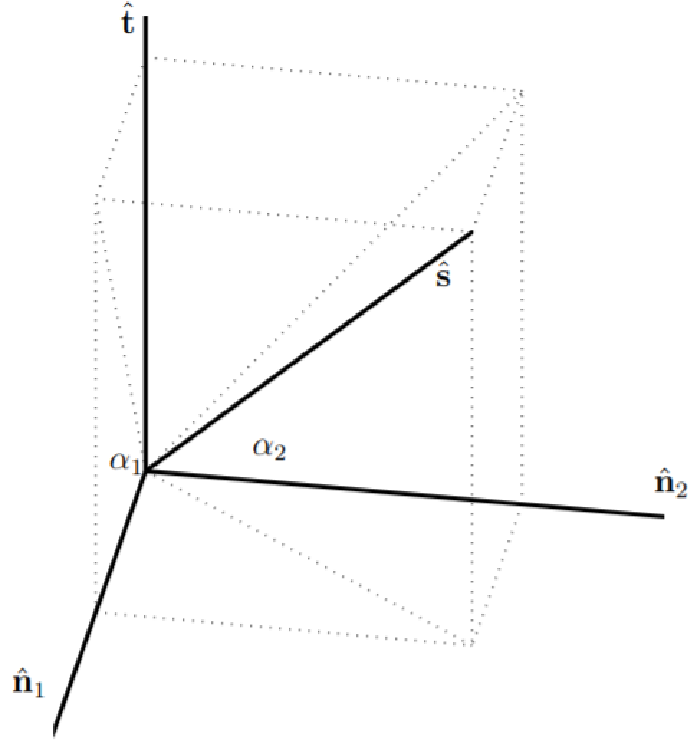
Photodiode Pyramid Equations (Pair)



$$
\begin{aligned}
I_1(\alpha) &= I(0)\cos(\alpha_0 - \alpha) \\
I_2(\alpha) &= I(0)\cos(\alpha_0 + \alpha)
\end{aligned}
$$

$$
\begin{aligned}
\Delta I &= I_2 - I_1 \\
&= I(0)\left[\cos(\alpha_0 + \alpha) - \cos(\alpha_0 - \alpha)\right] \\
&= 2I(0)\sin\alpha_0 \sin\alpha \\
&= C\sin\alpha
\end{aligned}
$$

Photodiode Pyramid Equations (Pair)



$$\mathbf{s}_s^* = [1 \quad \tan\alpha_1/\tan\alpha_2 \quad \tan\alpha_1]^\mathsf{T}$$

$$\mathbf{s}_s = \frac{[1 \quad \tan\alpha_1/\tan\alpha_2 \quad \tan\alpha_1]^\mathsf{T}}{\sqrt{\mathbf{s}_s^{*\mathsf{T}}\mathbf{s}_s^*}}$$

Pyramid Base Design

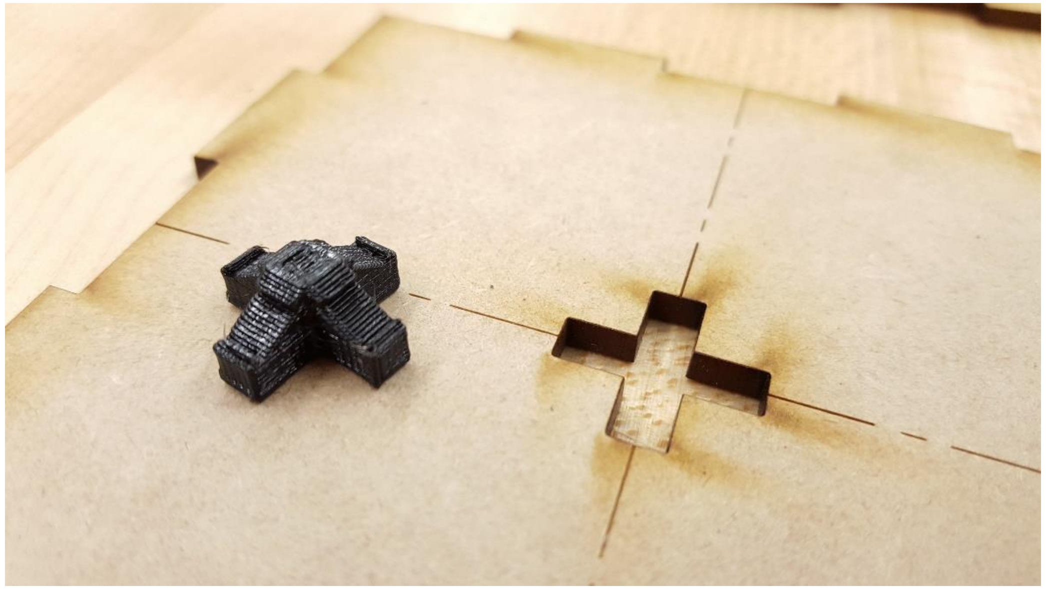
The angle α_o was picked based on the sensitivity of the photodiode. It was decided that a 30° angle would still place the sensor at a sensitivity of 80% of its original value.

- Sensitivity was determined from the diagram included in a previous slide.

This pyramid was meant to be a proof-of-concept so the design itself was not optimized for performance.

3D Printed.

45 degree Field of View.



Amplifying Circuit

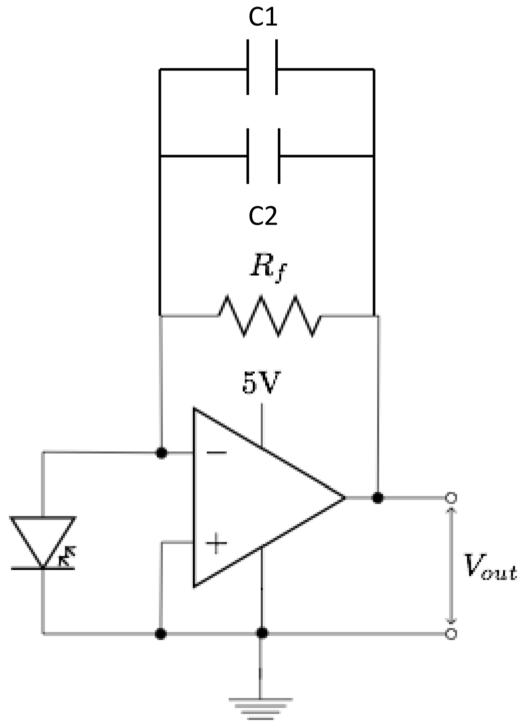
The signal from the photodiodes was to small to be read by an Arduino.

The signal was amplified to 5V using an operational amplifier and the circuit shown on the left.

This circuit has to be repeated for each photodiode included in the setup.

The components are:

- C1 = 0.001uF and C2 = 0.1uF
- Rf = 1MΩ
- OP-AMP = LTC 1050



Testing the Sensors

A full attitude solution cannot be obtained from a single vector and adding additional sensors in order to get this solution would have introduced more error/uncertainty in the results of our experiment.

It was decided to look at the deviation in the components of the measured and theoretical sun vectors instead as a method to analyze the errors in the measured sun vector.

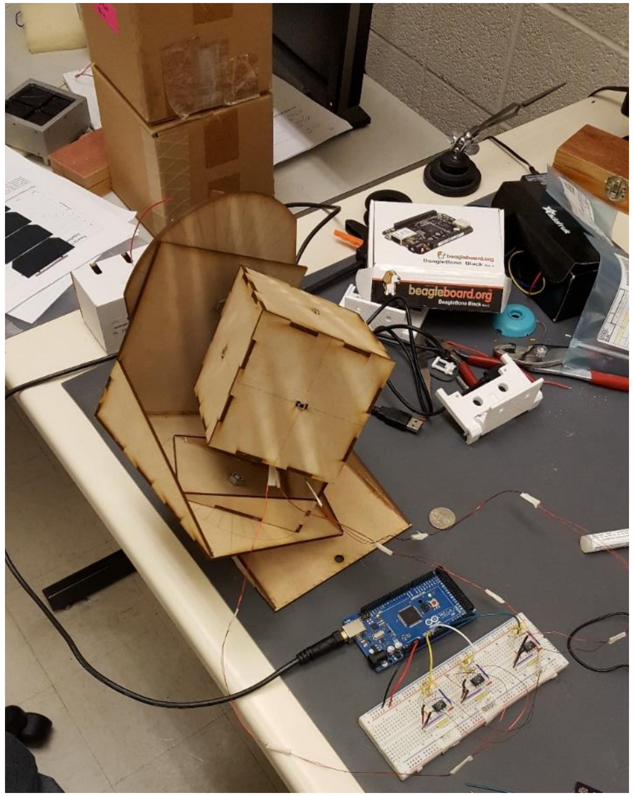
Each trial was performed by variating the pitch angle of the setup while keeping the roll and yaw angles constant. The percent difference in between theoretical and measured vectors was then recorded.

Thirty second trials were conducted and the mean value for the measured vectored was used for the results.

Experimental Setup

The setup consisted of:

- A light source to simulate the incident sunlight.
- A 3-axis of freedom test stand.
- An Arduino MEGA.
- A 1U mock-up for the sensors for each configuration.
- Amplifying circuit.
- MATLAB code for data processing.



3-Axis of Freedom Test Stand

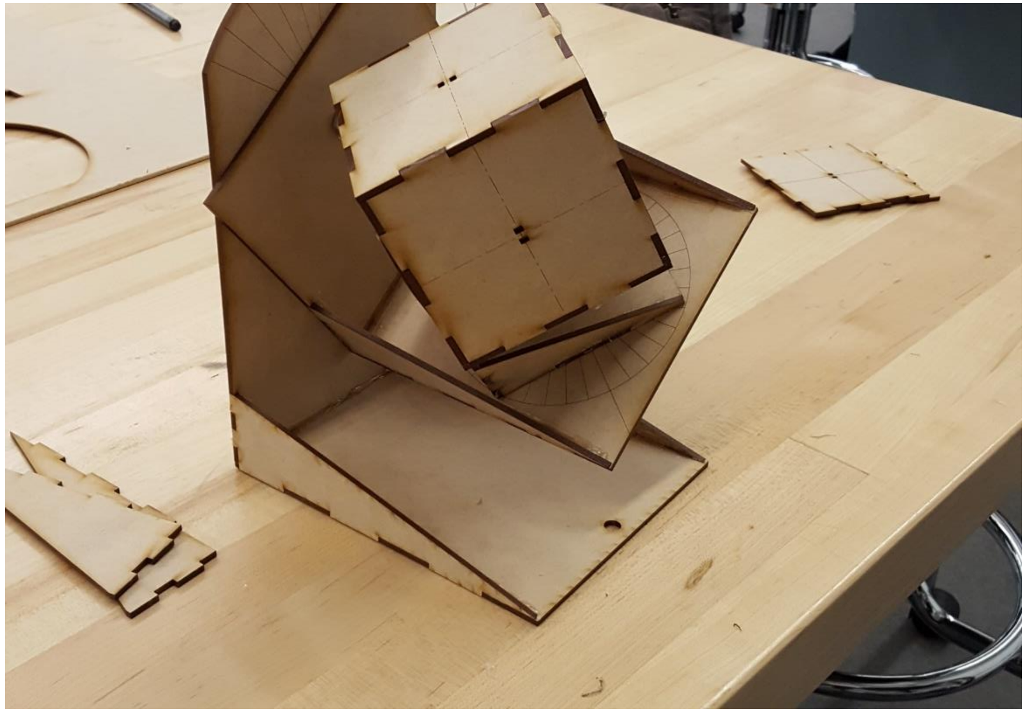
Allows for pitch, yaw, and roll rotations.

Used to determine the theoretical sun vector based on the Euler Angle rotations.

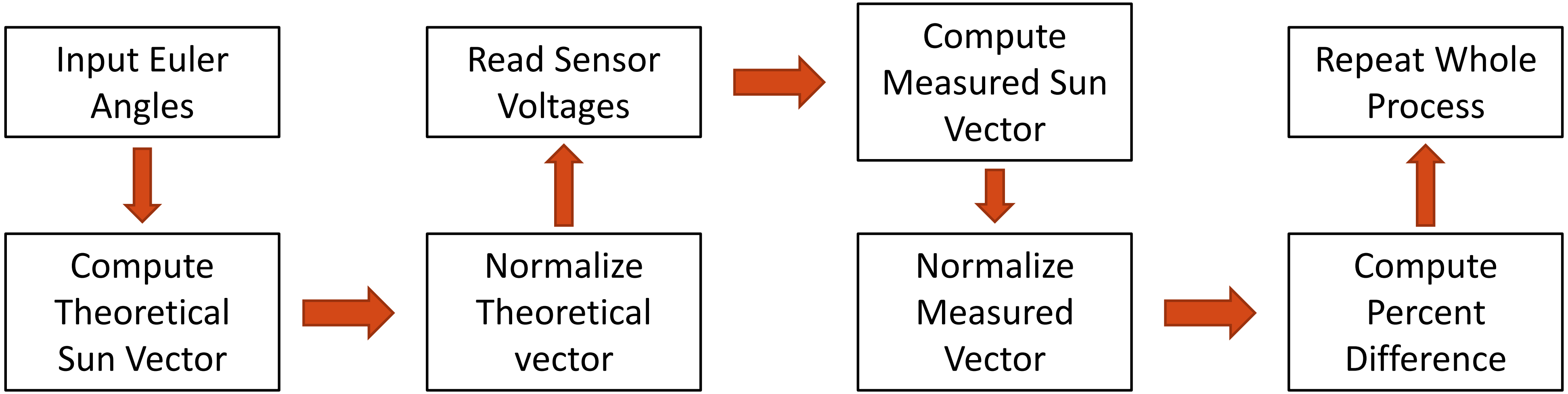
Designed around a RxRzRy rotation matrix: pitch first, then yaw, then roll.

Euler angles are laser printed on the sides in order to maintain accuracy.

Light source kept at (0 0 1) but the rotations simulate the body moving in space. A rotation matrix is then used to convert the (0 0 1) vector into a new vector in the new frame.



MATLAB Code Structure



Trials

SINGLE PYRAMID

1 – Axis Movement
- Roll = 0 and Yaw = 0

2 – Axis Movement
- Roll = 10 and Yaw = 0
- Roll = 30 and Yaw = 0

3 – Axis Movement
- Roll = 10 and Yaw = 30
- Roll = 30 and Yaw = 30

Pitch was varied from 0 to 40 degrees on each trial. This is because angles greater than 45 exceed the Field of View of the Pyramid.

SINGLE PHOTODIODE PER FACE

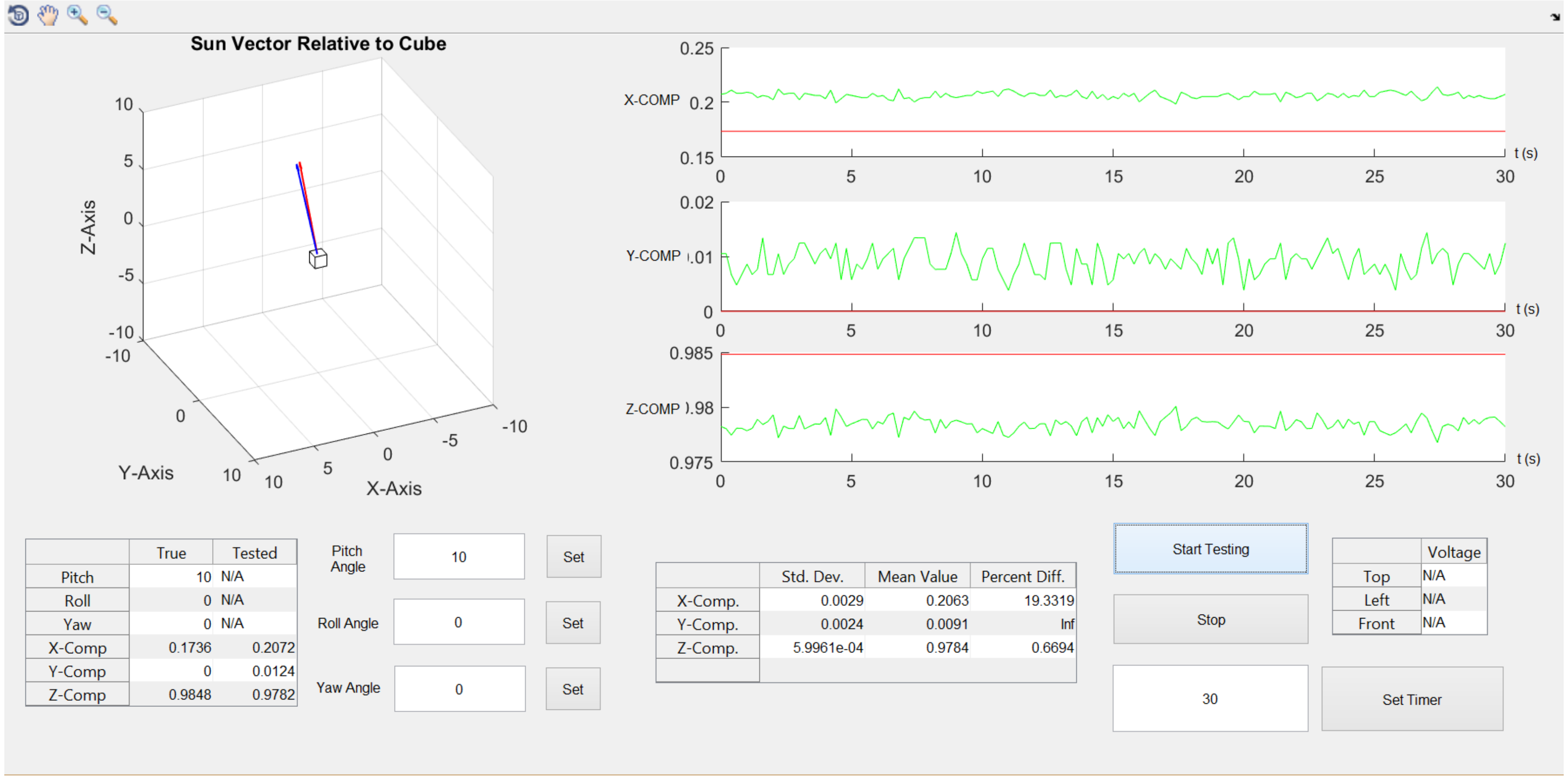
1 – Axis Movement
- Roll = 0 and Yaw = 0

2 – Axis Movement
- Roll = 30 and Yaw = 0
- Roll = 60 and Yaw = 0

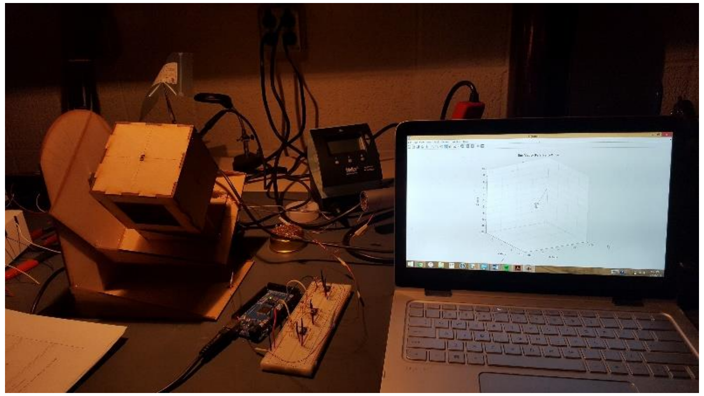
3 – Axis Movement
- Roll = 30 and Yaw = 30

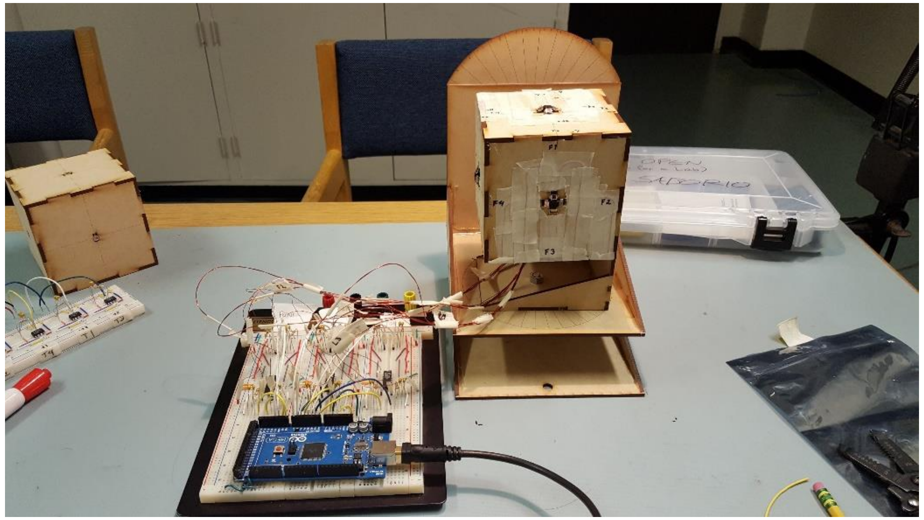
Pitch was varied from 0 to 65 on each trial. There was no technical Field of View for this configuration so a wider range for pitch angles was permitted.

Sample Output from GUI

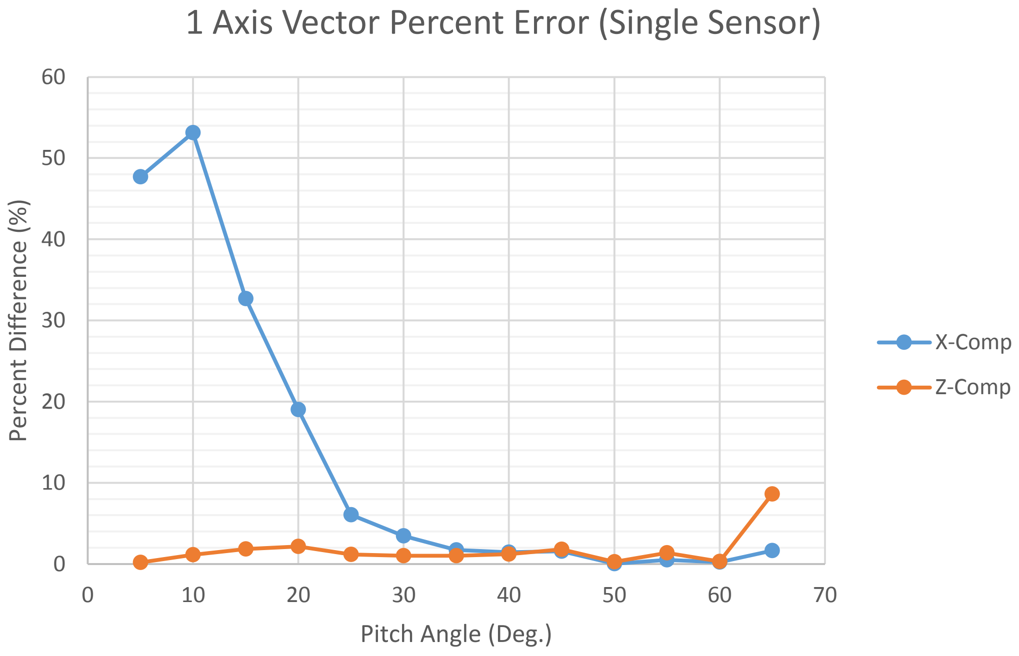


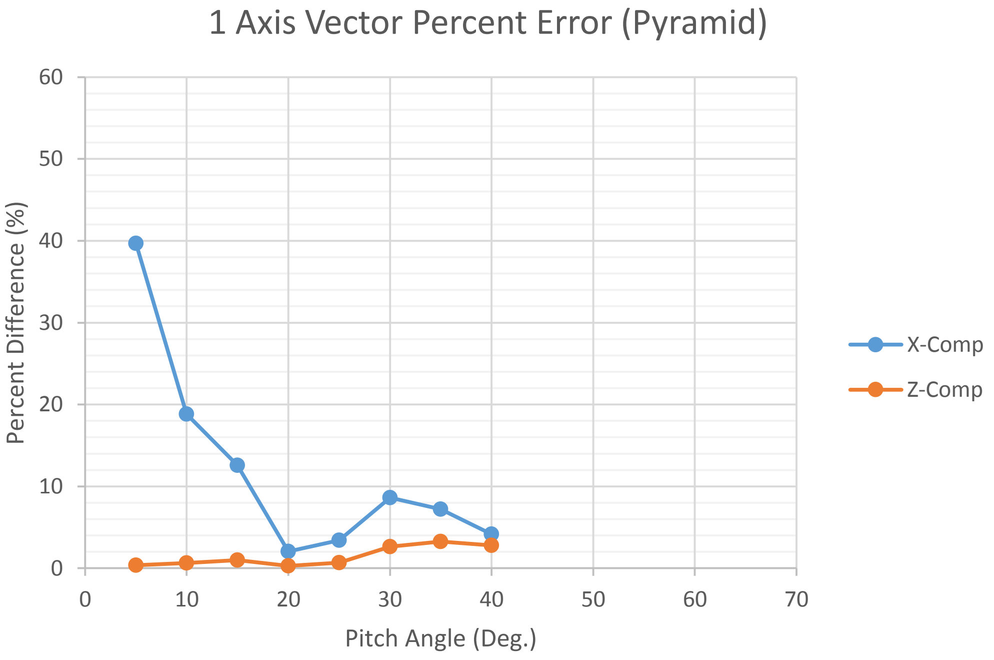
Sample Test Setup





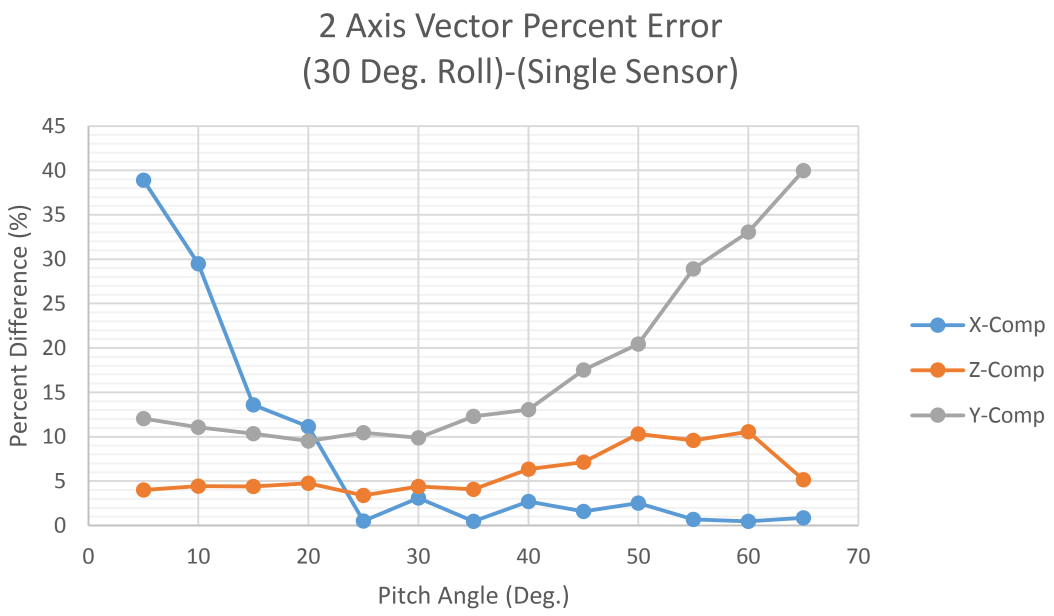
1-Axis Results (P, Y-0, R-0)

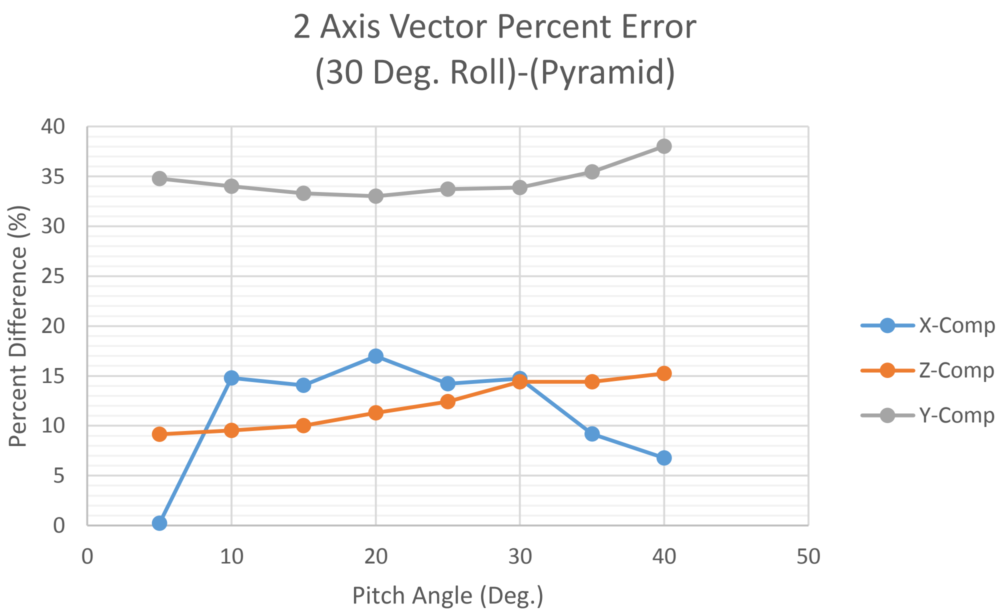




2-Axis Results (P, Y-0, R-30)

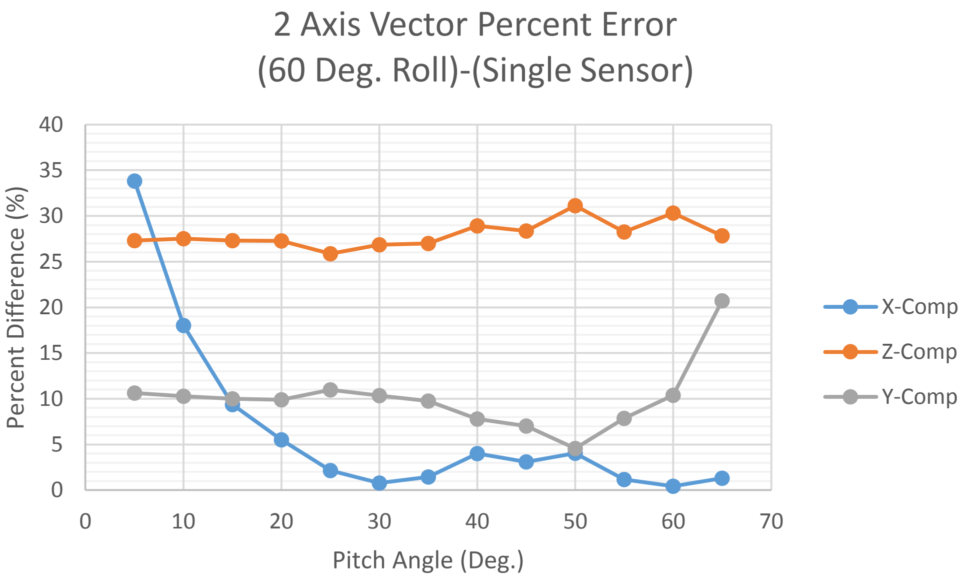
There was a higher uncertainty on the roll axis than the pitch axis. This could have been due to the distribution of the incoming light from the lamp not being symmetrical.

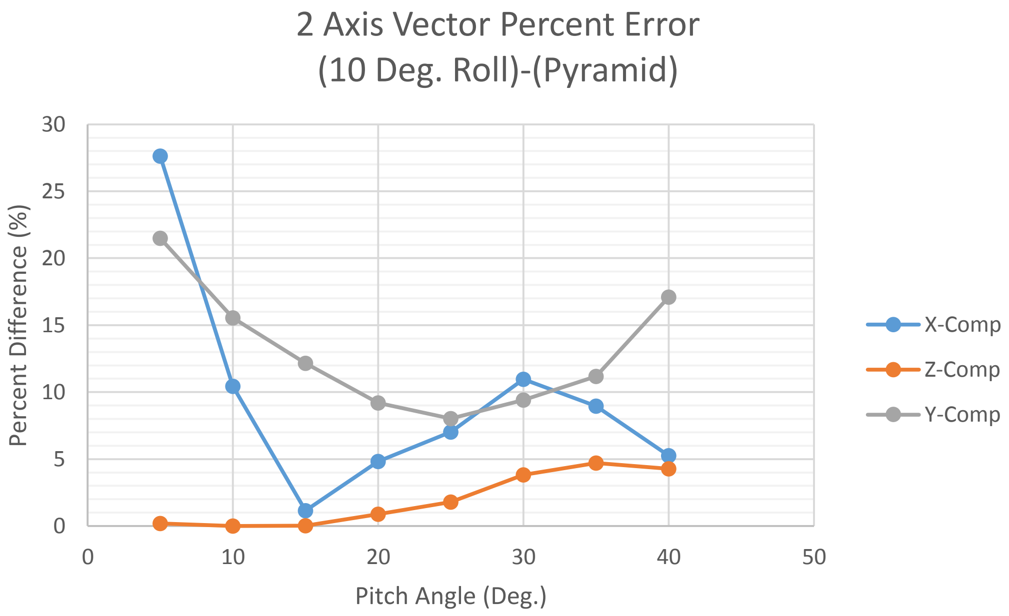




Additional 2-Axis Results

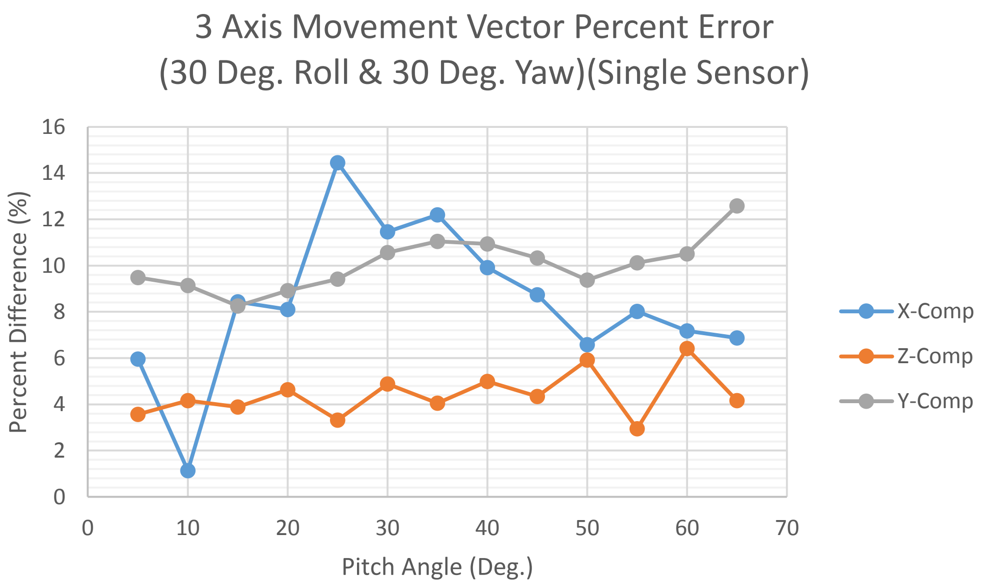
The testing conditions for these two results do not match because of the Field of View problem resulting from the Pyramid Configuration. The Single Sensor configuration was tested first and the FOV was not accounted for.

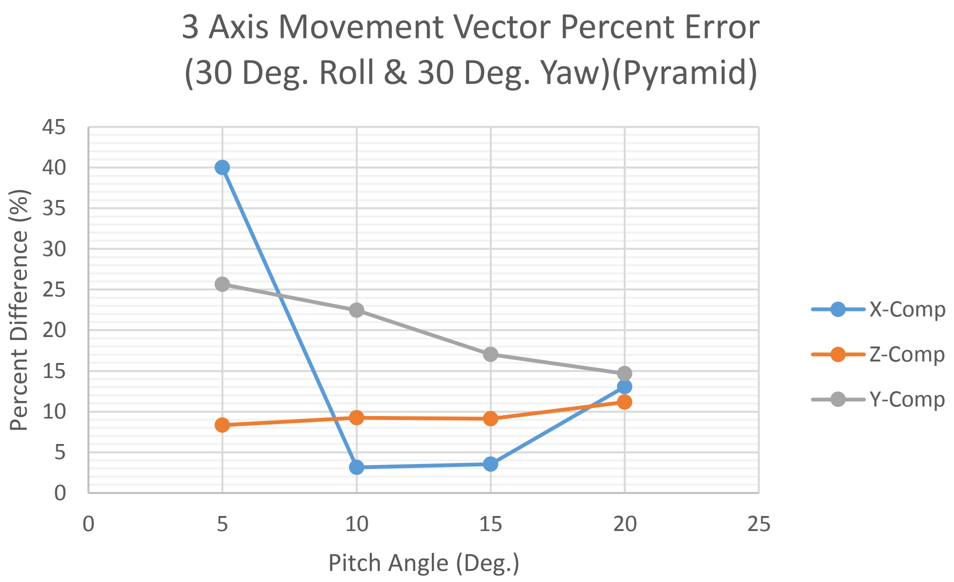




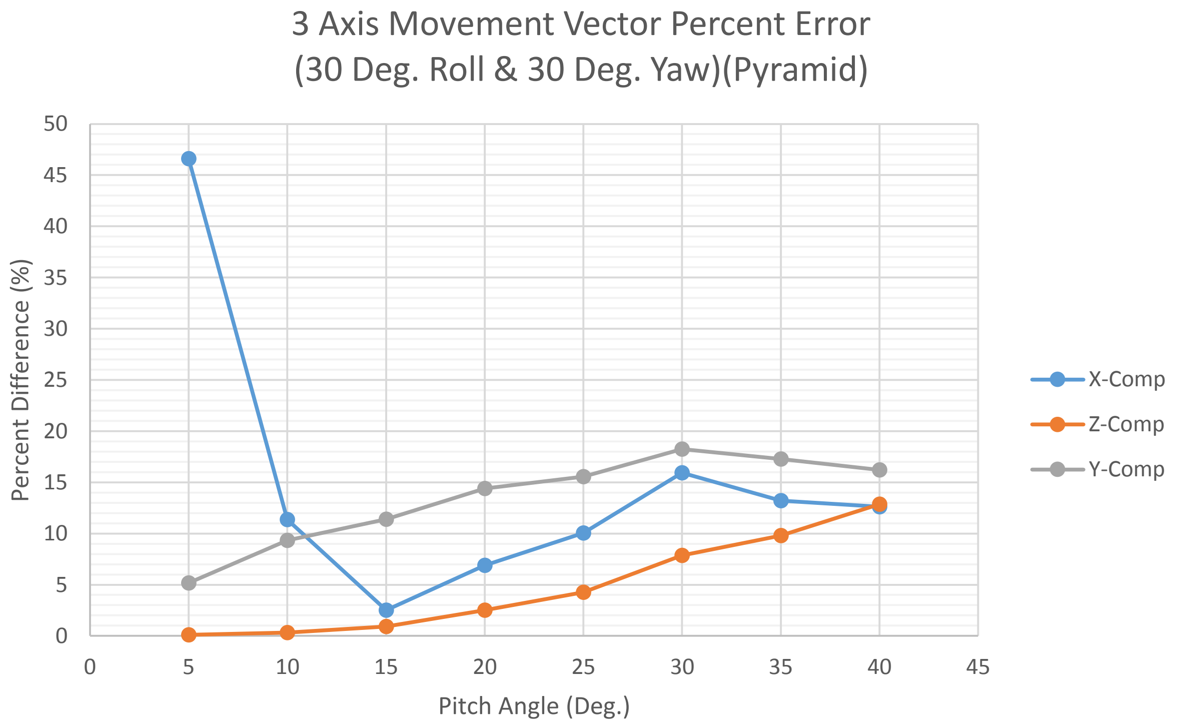
3-Axis Results (P, Y-30, R-30)

The testing for the Pyramid configuration had to be cut short because at an orientation of (P-20, Y-30, R-30) the FOV of the sensor was exceed. Hence, a second trial at smaller angles was done instead for the 3-Axis rotation.





3-Axis Results (P, Y-30, R-10)



Conclusions from Results

A pattern for the single sensor configuration could be identified for the 1-Axis and 2-Axis rotations. One of components remains constant but the other two are inversely related; as one component increases in accuracy the other one loses accuracy.

Overall the Pyramid configuration seems to do poorly at high angles close to the Field of View when compared to the single sensor configuration. That being said, the configuration does relatively well at smaller angles.

Field of View poses a challenge when incorporating a configuration in the satellite. Voltage thresholds have to be set for each Pyramid/Sensor based on the properties of the sensor in order to keep accuracy within a range. This results in the generalization of sensor behavior.

High percent differences are less relevant at lower angles. For example, at a small angle 50% could refer to the difference between 0.001 and 0.002.

At high angles we need a rough estimate of where the sun is, once the controls of the satellite start translating the satellite towards the sun, the accuracy will increase.

Proposed Setup for EXACT/SOCRATES

We have to take into account the previously outlined constraints.

Pyramid configuration seems to be an appropriate choice for both missions. It will not provide a full coverage of the satellite but can be used to increase the accuracy of the sun vector measurement once the satellite is pointed close to the sun.

Lack of coverage can be counteracted by the current ADCS code which already provides sun vector measurements. Outside the configuration’s FOV the satellite can use the current ADCS code to move the satellite back to the FOV.

This configuration would be the less invasive setup to implement.

Proposed Placement

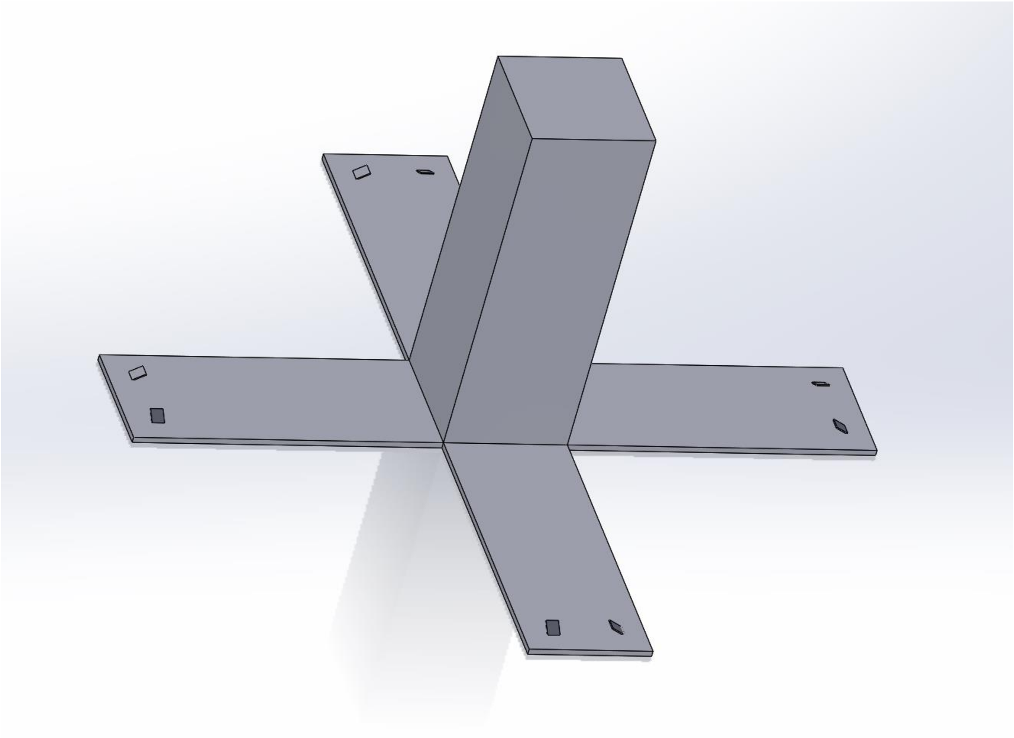
Include two pyramids and take the average vector measurement from the two.

Divide the two pyramids into two sections.

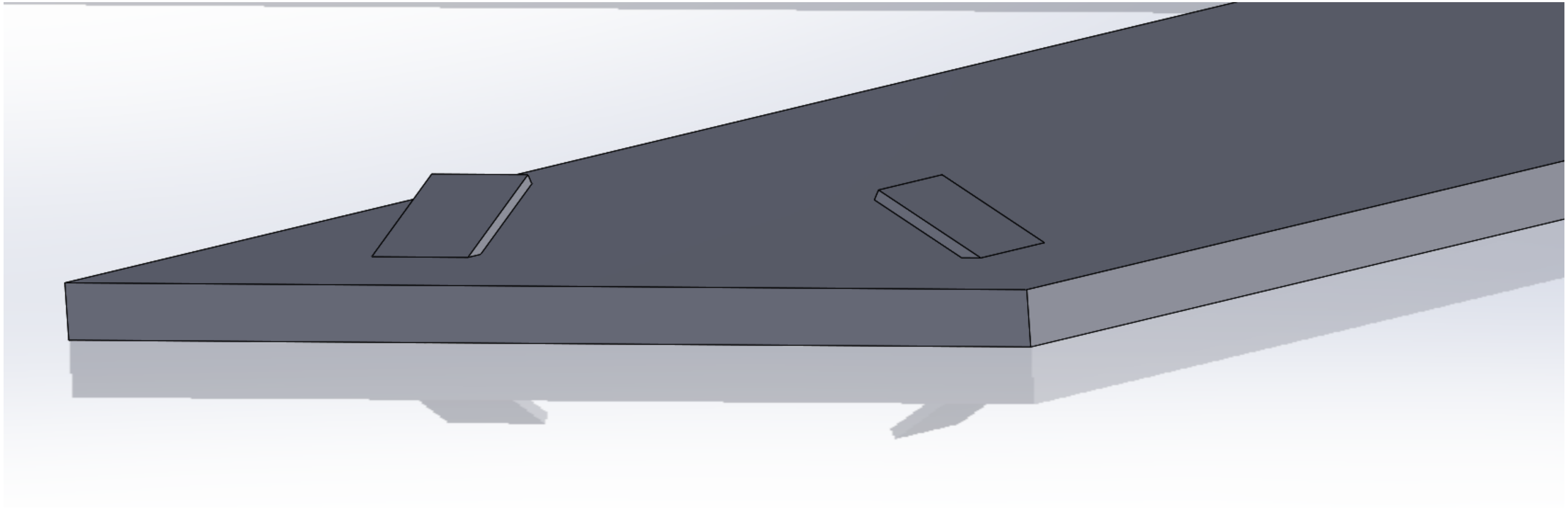
Place these sections in the solar cell PCBs.

- Noise from the sensor should be minimal
- Noise from the cells can be avoided
- Provides a connection from the exterior of the satellite to the interior without having to change the structure

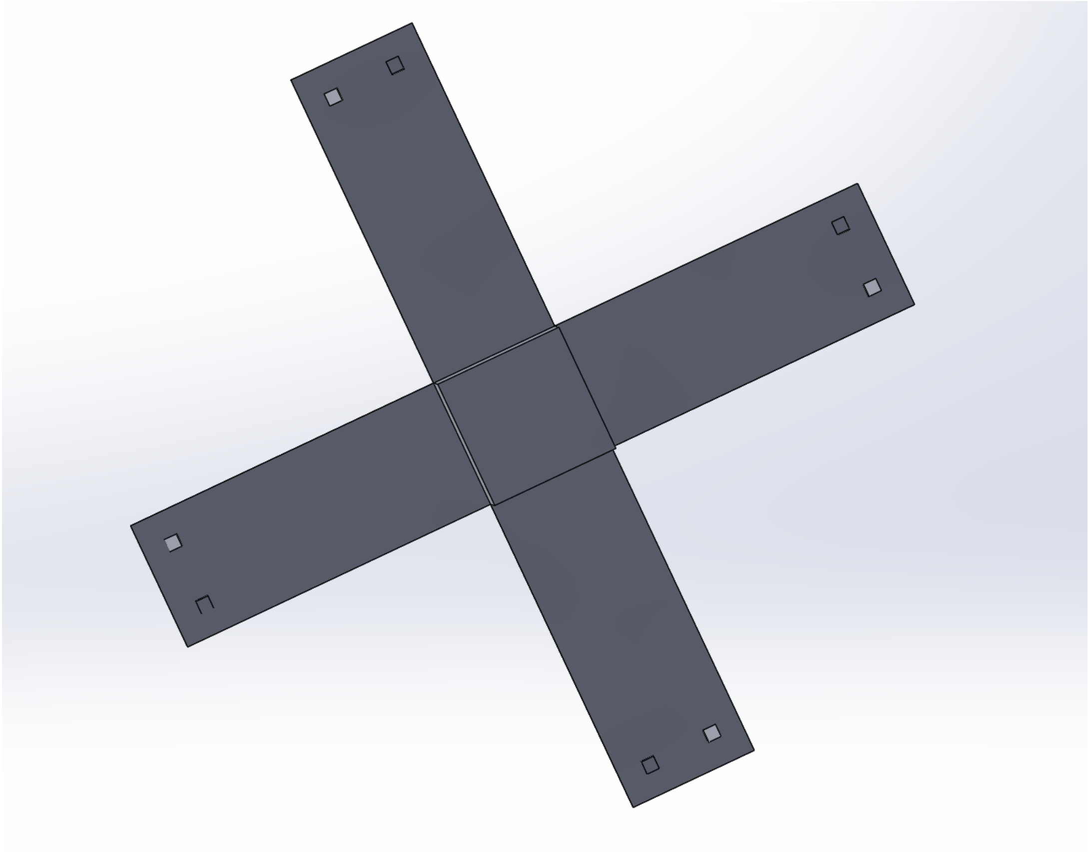
Trying to locate a source millions of kilometers away so the sensors can be assumed to be at the origin.

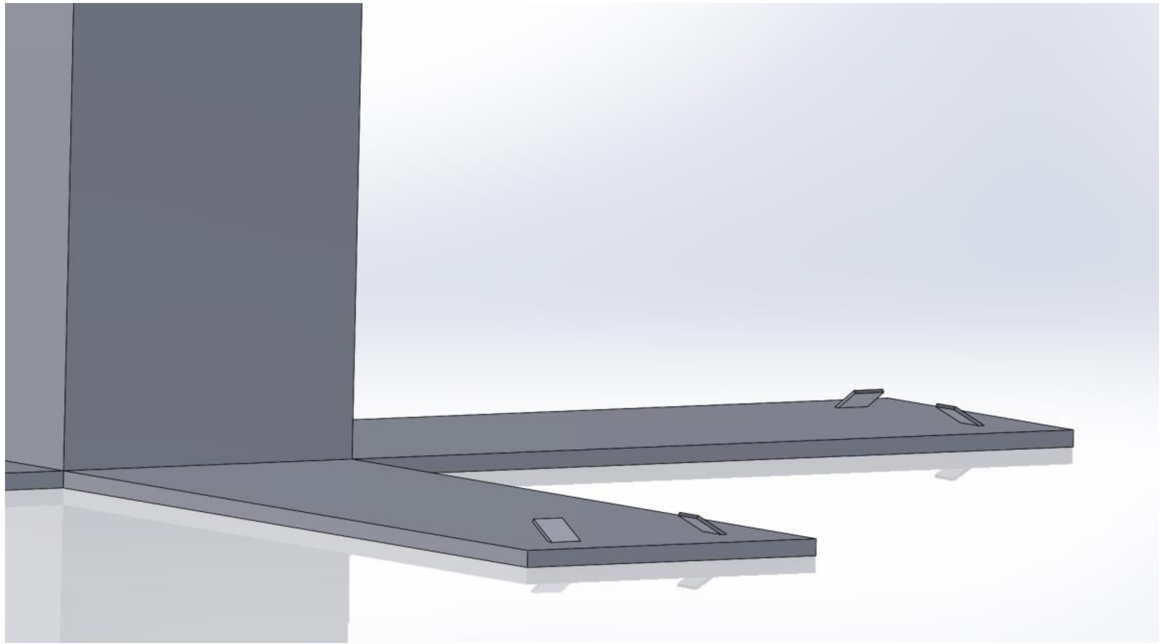


Proposed Placement



Proposed Placement





Requirements for the Configuration

Hardware:
- Multiplex
- 2 quad OP-AMPS
- 16 capacitors
- 8 resistors (or digital potentiometer)
- 8 photodiodes
- 5V supply to OP-AMPS
- Traces connecting to BeagleBone’s analog input
- Angled mounts

There is space left in the Magnetorquer Board that could be used for this purpose.

Software:
- Solar model
- Earth Albedo model
- In-orbit calibration protocol
  - Single photodiode place flat on solar cell PCB
  - Digital potentiometer
  - Adjusts the gain of the amplifying circuit
- Necessary modifications to the ADCS code

Conclusion

Questions or comments?

References

Hall, Christopher D. "Chapter 4: Attitude Determination." *Spacecraft Attitude Dynamics and Control*. N.p.: n.p., 2012. 4-1--19. Print.

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Springmann, John C, and James W Cutler. *Photodiode Placement & Algorithms for CubeSat Attitude Determination*. Michigan Exploration Lab , 2012, *Photodiode Placement & Algorithms for CubeSat Attitude Determination*, mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2012/Springmann_Photodiode_Determination.pdf.